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Recycling of manure nutrients: use of algal biomass from dairy manure treatment as a slow release fertilizer

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Abstract

An alternative to land spreading of manure is to grow crops of algae on the N and P present in the manure and convert manure N and P into algal biomass. The objective of this study was to evaluate the fertilizer value of dried algal biomass that had been grown using anaerobically digested dairy manure. Results from a flask study using two soils amended with algal biomass showed that 3% of total algal nitrogen (N) was present as plant available N at day 0. Approximately 33% of algal N was converted to plant available N within 21 days at 25 °C in both soils. Levels of Mehlich-3 extractable phosphorus (P) in the two soils rose with increasing levels of algal amendment but were also influenced by existing soil P levels. Results from plant growth experiments showed that 20-day old cucumber and corn seedlings grown in algae-amended potting mix contained 15–20% of applied N, 46–60% of available N, and 38–60% of the applied P. Seedlings grown in algae-amended potting mixes were equivalent to those grown with comparable levels of fertilizer amended potting mixes with respect to seedling dry weight and nutrient content. These results suggest that dried algal biomass produced from treatment of anaerobically digested dairy manure can substitute for commercial fertilizers used for potting systems.
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Keywords: Dairy manure; Organic fertilizer; Anaerobic digestion; Algae; Nitrogen; Phosphorus; Corn; Cucumber

1. Introduction

Controlling the input of nitrogen (N) and phosphorus (P) from dairies and other livestock operations into adjacent aquatic systems and into the atmosphere poses both technical and economic challenges to the agricultural community (Adey et al., 1993; Kaiser, 2001; Van Horn et al., 1994). During storage and land application of manure effluents, large amounts of N are lost to the atmosphere due to volatilization of ammonia. Ecologically sound manure management on farms is vital to minimize loses of valuable plant nutrients and to prevent nutrient contamination of the surrounding watershed.

An alternative to land spreading of manure is to grow crops of algae on the N and P present in the manure and convert manure N and P into algal biomass. Most efforts in using algae for wastewater treatment have been focused on tertiary treatment of municipal waste effluents using suspended microalgae (Benemann and Oswald, 1996). Wastewater treatment using attached algae has also been reported and has potential advantages in how the algal biomass is harvested and dried (Hoffman, 1998). One technology using periphyton, termed algal turf scrubbers (ATS) (Adey and Hackney, 1989; Adey and Loveland, 1998), is relatively simple in design and yields an algal biomass that can be easily harvested on adapted farm-scale equipment. An ATS is essentially an artificial stream designed to promote biological wastewater treatment using periphyton. The essential elements of the ATS system are a solid support for the growth and harvest of periphyton, a wave surge and optimal light (Craggs et al., 1996).

The general goal of our research is to adapt and develop aquatic plant and algal treatment systems for nutrient recovery from animal manure. Previous work in this laboratory has demonstrated the use of ATS periphyton to remove N and P from dairy manure effluents (Kebede-Westhead et al., 2003; Mulbry and Wilkie, 2001; Wilkie and Mulbry, 2002). Algal biomass recovered from such systems has a variety of potential

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on- and off-farm uses. Among these is using the algal biomass as a slow release fertilizer. The use of blue green algae as soil conditioning amendments and as biofertilizers for rice cultivation has been reported previously (Metting, 1996; Metting et al., 1990). However, there has been no research on the fertilizer value of algal biomass from treatment of animal manure. The objective of this study was to evaluate the fertilizer value of dried algal biomass that had been grown on anaerobically digested dairy manure.

2. Methods

2.1. Production of algal biomass

Algal biomass was produced from laboratory-scale algal turf scrubbers (ATS) using anaerobically digested dairy manure collected from the Dairy Research Unit of the USDA's Beltsville Agricultural Research Center in Beltsville, Maryland at a manure loading rate corresponding to approximately 1 g total N (TN) m^{-2} day^{-1} as previously described (Kebede-Westhead et al., 2003; Mulbry and Wilkie, 2001; Wilkie and Mulbry, 2002). The biomass was sieved through a 2 mm mesh screen to approximately 10% solids content, air-dried for 48 h, ground using a Wiley Mill, and sieved using a 2 mm sieve. ATS biomass production was about 7 g DW m^{-2} day^{-1}. Elemental compositions of the dried ATS biomass and the anaerobically digested dairy manure used to grow the algal biomass were determined using ICP (induced coupled plasma) analysis. Garden-tone 4-6-6 fertilizer (Espoma Co., Millville, NJ) used in growth chamber experiments was analyzed for total N and P content after total Kjeldahl block digestion by flow injection analysis. According to the label, the fertilizer contained 4% TN (2.5% ammonia-N; 0.3% other water soluble N; 1.2% water insoluble N), 6% available phosphate (P_2O_5), and 6.0% soluble potash (K_2O).

2.2. Algal N and P mineralization rate determination

A laboratory incubation study was conducted to determine the N and P mineralization rates of dried ATS biomass in two soils. Sassafras sandy loam and Codorus silt loam soils (Table 1) were air-dried, crushed and passed through a 2 mm sieve (Sikora and Enkiri, 2003). One hundred gram aliquots of these soils were amended with either 0.75 or 1.5 g dried ATS biomass and transferred to biometer flasks (Bartha and Pramer, 1965). These amendments corresponded to total loadings (in mg kg^{-1}) of 338 N, 55 P and 676 N, 110 P, respectively. CaO was added to each flask to achieve a soil pH of 7.0. This procedure was repeated for all of the treatment flasks. An equal number of control flasks containing Sassafras and Codorus soils plus CaO were also prepared. All flasks were brought to −33 kPa moisture, weighed, and incubated at 25 °C. Flasks were weighed weekly and distilled water was added as needed to bring flasks to initial weights. Three control flasks and three flasks from each treatment were sampled at 0, 7, 21 and 42 days. For determination of nitrate-N and ammonium-N, a 10 g sample from each flask was extracted with 100 ml 2 M KCl on a rotary shaker for 30 min. Extracts were filtered using 0.45 μm membrane and the pH of the filtrates was adjusted to 3–5 with H_2SO_4 as needed for preservation. Filtrates were stored frozen until analysis. Ammonium-N and nitrate-N were determined colorimetrically by flow injection analysis (Lachat Instruments, Milwaukee, WI). For determination of orthophosphate and Mehlich-3 extractable P, 10 g soil samples were extracted either distilled water or Mehlich-3 extractant (Mehlich, 1984; Wolf and Beegle, 1994) following the procedure outlined above, but with no adjustment of extractant pH. Orthophosphate was determined colorimetrically by flow injection analysis. Moisture analyses of samples were determined on samples dried overnight at 105 °C.

Table 1
Constituents of Sassafras and Codorus soils

Constituent	Concentration	
	Sassafras soil[a]	Codorus soil
pH	5.4	5.7
Total organic carbon	15.2 g kg^{-1}	12.6 g kg^{-1}
Total nitrogen	2.0 g kg^{-1}	1.0 g kg^{-1}
Total phosphorus	0.35 g kg^{-1}	0.37 g kg^{-1}
Mehlich-3 extractable P	0.126 g kg^{-1}	0.009 g kg^{-1}
Water-extractable P	0.006 g kg^{-1}	0.0002 g kg^{-1}
Total potassium	0.19 g kg^{-1}	n.d.[b]
Total magnesium	50 mg kg^{-1}	n.d.
Total copper	5.4 mg kg^{-1}	n.d.
Zinc	20.4 mg kg^{-1}	n.d.
Cadmium	0.1 mg kg^{-1}	n.d.

[a] Sikora and Enkiri (2003).
[b] n.d.: not determined.

2.3. Growth chamber study

Based on the net mineralizable N value from ATS biomass obtained from the soil incubation study, growth chamber experiments using cucumber (*Cucumis satious*) and corn (*Zea mays*) were conducted to compare plant growth and nutrient uptake using a commercial potting mix amended with either ATS biomass and or a roughly comparable commercial fertilizer. For cucumber plant growth experiments, 80 g ProMix BX potting mix (Premier Horticulture, Quebec, Canada) was amended with three levels of dried ATS biomass or two levels of a roughly comparable commercial fertilizer (Garden-tone 4-6-6). The elemental composition of the dried algal biomass, the dairy manure used to grow the algae, and Garden-tone fertilizer are listed in Table 2. Each potting mixture was wetted with 200 ml distilled water to achieve approximately −33 kPa, and the wetted mix was added to 10 cm plastic pots. Five cucumber seeds (Market More 76, Meyer Seeds, Baltimore, MD) were planted in each pot and the pots were placed in a growth chamber that was maintained at 25 °C during 16 h of illumination and at 20 °C for the 8-h dark period. Light intensity from a mixture of high pressure sodium and metal halide lamps was approximately 600 $\mu mol\ s^{-1}\ m^{-2}$. The six treatments consisted of three levels of ATS biomass (2.8, 5.5, and 11 g biomass per pot corresponding to field application rates of 42, 83, and 164 kg available N ha^{-1}), two levels of Garden-tone 4-6-6 fertilizer (1.25 and 2.5 g fertilizer per pot corresponding to field application rates of 37.5 and 75 kg available N ha^{-1}), and control pots containing non-amended potting mix. There were five pots for each treatment.

For corn plant growth experiments, 225 g ProMix BX potting mix was amended with two levels of dried ATS biomass or two levels of a Garden-tone 4-6-6 fertilizer. Each mixture was wetted with 550 ml distilled water to achieve approximately −33 kPa, and the wetted mix was added to 15 cm plastic pots. Five corn seeds (Silver Queen, Wetsel Inc., Harrisonburg, VA) were planted in each pot and the pots were placed in a growth chamber that was maintained as described above. The seedlings were thinned to two seedlings per pot after 7 days. The five treatments consisted of two levels of ATS biomass (10 and 20 g biomass per pot corresponding to field application rates of 75 and 150 kg available N ha^{-1}), two levels of Garden-tone 4-6-6 fertilizer (5.5 and 11 g fertilizer per pot corresponding to field application rates of 82 and 165 kg available N ha^{-1}), and control pots containing non-amended potting mix. There were five pots for each treatment.

Pots were manually watered every 24–48 h by weighing and adding distilled water to achieve the 0 time weight. After 20 days, seedlings were harvested by cutting them off at the soil level, dried for 48 h at 70 °C in a forced air oven, weighed, and ground using a Wiley Mill. Ground samples were analyzed for total N and P content after total Kjeldahl block digestion by flow injection analysis. Roots from approximately half of the cucumber replicates were separated from soil using a 2-mm sieve and then washed, dried, weighed, and analyzed using the same techniques as those for the seedlings.

Table 2
Elemental composition of anaerobically digested dairy manure, algal turf scrubber (ATS) biomass and Garden-tone 4-6-6 fertilizer

Constituent	Dairy manure, $mg\ l^{-1}$	ATS biomass, $mg\ kg^{-1}$	Fertilizer, $mg\ kg^{-1}$
N	2760	45,100	48,000
P	332	7300	25,200
K	2234	9100	49,800
Ca	860	5470	30,000
Mg	260	1900	5000
Si	115	230	n.d.[a]
Fe	20.6	1240	10,000
Al	20.6	440	n.d.
Mn	9.2	250	500
Zn	8.6	270	500
Cu	3.7	84	500
Ba	0.94	30	n.d.
B	1.6	20	200
Cd	0.08	0.32	n.d.
Pb	0.05	6.5	n.d.
Ni	0.09	3.8	n.d.
Mo	0.06	2.5	5

Constituent values for manure and ATS biomass were determined in our laboratory. Fertilizer N and P values were determined in our laboratory other fertilizer constituent values are from the product label.

[a] n.d.: not determined.

2.4. Statistical analyses

The data for the variables mineral N and Mehlich P from the soil mineralization experiments were analyzed with Proc Mixed (SAS Institute, 1999) as three-factor linear models where soil, amendment and day were the factors (Table 3). For mineral N the day zero values were not included in the analysis as there was little difference between treatments at this timepoint. The biomass and plant N data from the plant growth experiments were analyzed separately for corn and cucumber using Proc Mixed as a one-factor linear model where the application and source combinations were coded into treatments levels (not shown). In each analysis, the assumptions of the general linear model were tested. To correct variance heterogeneity the variance grouping technique was used. Since treatments were statistically significant (p-values < 0.0001), mean comparisons were done with Sidak adjusted p-values so that the experimentwise error was 0.05.

3. Results

3.1. Mineralization of ATS biomass N and P in Sassafras and Codorus soils

A soil incubation study was used to determine net mineralizable N in dried ATS biomass using two local soils. Approximately 3% of the total algal N was present as mineral N at day zero (Table 4). After 21 days an additional 26–30% of total N was mineralized for a total of 30–33% of total N as plant available N (Table 4, Fig. 1 panel A). There was no significant difference at the 5% level between net mineral N levels of ATS biomass in the two soils.

Incubated soils were also extracted for Mehlich-3 extractable and water-extractable P. Levels of Mehlich-3 extractable P (a measure of plant available P) increased

Table 3
Three-way ANOVA testing effects of soil, amendment, and time on levels of mineral N (NH_4-N and NO_3-N) and Mehlich-3 P in limed Sassafras and Codorus soils and in limed soils amended with two levels of algal turf scrubber biomass

Source	Mineral N			Mehlich-3 P		
	DF	F-value	p-value	DF	F-value	p-value
Soil	1	0.08	0.7908	1	1906.16	<0.0001
Amendment	2	189.07	<0.0001	2	142.75	<0.0001
Day	2	81.55	<0.0001	3	47.06	<0.0001
Soil × amendment	2	0.35	0.7214	2	16.35	0.0001
Soil × day	2	4.86	0.0455	3	25.92	<0.0001
Amendment × day	4	28.21	<0.0001	6	3.43	0.0165
Soil × amendment × day	4	3.64	0.0552	6	4.19	0.0065

Table 4
Comparison of mean levels of mineral N (NH_4-N and NO_3-N) (mg flask^{-1}) in limed Sassafras and Codorus soils and in limed soils amended with two levels of algal turf scrubber biomass

Level		Day[1]		
		7	21	42
Soil				
Codorus		12.14 a[2] y[3]	16.16 a x	15.10 a xy
Sassafras		9.90 b y	16.43 a x	16.20 a x
Amendment	Applied N			
0	0	3.45 c z	4.76 c y	6.02 b x
750	33.8	10.59 b y	16.03 b x	14.10 ab xy
1500	67.6	19.01 a y	28.10 a x	26.82 a xy

[1] Day zero values were not included in the statistical analysis. Mean mineral N values at day zero for flasks containing soils amended with 0, 750, and 1500 mg algal biomass were 1.28, 2.37, and 3.54, respectively.
[2] Means within day with different a, b, c letters are different at the 0.05 significance level.
[3] Day means within level with different x, y, z letters are different at the 0.05 significance level.

with algal amendment and with incubation time but were also influenced by the existing soil P levels (Table 5, Fig. 1 panel B). In Sassafras soil at the highest amendment rate, approximately 52% of algal P was present as Mehlich-3 extractable P at the beginning of the experiment. This value rose to 75% within 21 days. In Codorus soil (a phosphorus deficient soil) (Table 2), only 39% of algal P was present as Mehlich-3 extractable P at the beginning of the experiment and this value did not increase significantly with 42 days. Water-extractable P levels in ATS biomass amended soils was variable but generally increased with algal amendment and accounted for approximately 5% of applied algal P throughout the incubation period (Table 5, Fig. 1 panel C).

3.2. Seedling growth experiments

Based on the above value of 33% for net mineralizable N from ATS biomass, growth chamber experiments using corn and cucumber were conducted to compare plant growth and nutrient uptake using a commercial potting mix amended with either ATS biomass and or a roughly comparable commercial fertilizer (Garden-tone 4-6-6). Results from both sets of plant experiments showed that seedling mass and nutrient content increased with increased algal or fertilizer amendment. Cucumber seedling mass increased linearly with increased available N up to 83 mg available N (equivalent to 83 kg available N ha^{-1}) but showed no increase at the highest level of algal amendment containing 164 mg available N (Table 6, Fig. 2). Net seedling N represented 46–53% of available algal N and 48–55% of available fertilizer N. Net seedling P represented 39–45% of algal P and 30–33% of fertilizer P (Table 6). There was no significant difference in seedling N between algal or fertilizer treated potting mixes based on available N added (Table 6, Fig. 2). However, seedling mass and seedling P values were higher in algal amended mixes than in fertilizer amended mixes based on applied P.

Roots from approximately half of the cucumber replicates were separated from the potting mixes, cleaned, dried and analyzed for total N and total P. Within this limited subset of samples, dried roots accounted for 15–20% of total plant mass, 15–20% of total plant N, and 14–26% of total plant P (data not shown).

Results with corn seedlings showed no significant difference in corn seedling mass or seedling N between algal or fertilizer amended potting mixes based on available N at the low amendment rate (165 mg per pot;

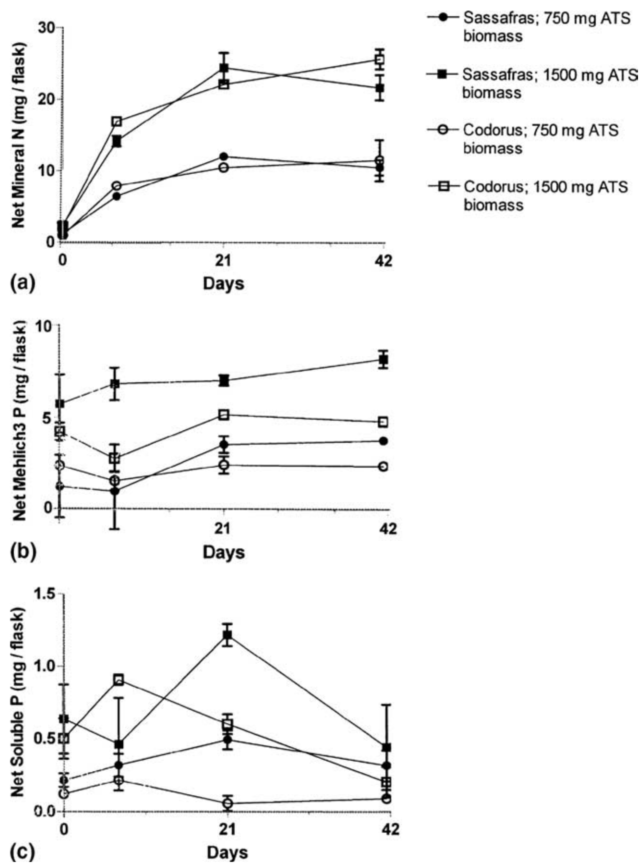

Fig. 1. Net mineral N (NH_4-N and NO_3-N), net Mehlich-3 extractable P, and net soluble P in two soils amended with two levels of algal turf scrubber (ATS) biomass. Net values (mean ± std. error) were calculated at each timepoint as treatment values minus values from flasks containing no amendment. Seven hundred and fifty milligrams ATS biomass contained 33.8 mg N and 5.5 mg P. One thousand five hundred milligrams ATS biomass contained 67.5 mg N and 11.0 mg P.

equivalent to approximately 82 kg available N ha^{-1}) (Table 7, Fig. 3). At the higher amendment rates, ATS amendment yielded higher seedling biomass but lower seedling N compared to a roughly comparable rate of fertilizer amendment (Fig. 3). Net corn seedling N represented 57–60% of available algal N and 64–65% of available fertilizer N. Net corn seedling P represented 42–61% of algal P and 27–40% of fertilizer P (Table 7).

4. Discussion

Our results demonstrate that ATS biomass was equal to fertilizer in supplying N and P to cucumber and corn seedlings in separate 20-day growth chamber studies. Both sources increased plant yield with increasing amendment rate in a commercial potting mix. ATS biomass has an advantage as a slow release fertilizer since only about 3% of the biomass N would be available as mineral N at the time of application. Applying dried algal biomass to soils would not result in NH_3 volatilization as is the case with manures (Thompson and Meisinger, 2002) and algal biomass may not have to be tilled into soil. This benefit may allow the algal biomass to be side-dressed into growing crops. Longer term field studies are needed to assess the effect of ATS biomass amendment on corn and vegetable yields.

Production of algal biomass from the treatment of dairy manure can be roughly estimated using published values of N excretion from dairy cows. Using values of approximately 300 g TN excreted $cow^{-1}\,day^{-1}$ (Van Horn et al., 1994) and ATS manure loading rates corresponding to 3 g TN $m^{-2}\,day^{-1}$ (Kebede-Westhead et al., 2003), the area needed for algal treatment of the manure effluent would be approximately 1 ha for every 100 animals. In Maryland, algal production could be expected to operate 9 months of the year at average production values of 15 g DW algal biomass $m^{-2}\,day^{-1}$ (equivalent to 150 kg DW $ha^{-1}\,day^{-1}$ or 40.5 mt DW $year^{-1}$). At these loading rates, algal biomass would contain approximately 7% N and 1% P and would contain approximately 50–70% of the original manure N and P (Kebede-Westhead et al., 2003). The volume of algal biomass from a 100 cow dairy would provide available N fertilizer equivalents for 6 ha of corn at

Table 5
Comparison of mean levels of Mehlich-3 P (mg $flask^{-1}$) in limed Sassafras and Codorus soils and in limed soils amended with two levels of algal turf scrubber biomass

Amendment	Applied P	Day			
		0	7	21	42
Codorus					
0	0	0.98 c[1] x[2]	0.82 b x	1.05 c x	1.13 c x
750	5.5	3.37 b x	2.35 ab x	3.47 b x	3.49 b x
1500	11.0	5.23 a xy	3.58 a y	6.23 a x	5.95 a x
Sassafras					
0	0	9.58 b x	9.73 b x	12.98 c x	12.79 c x
750	5.5	9.13 b y	8.71 b y	16.51 b x	16.55 b x
1500	11.0	15.35 a y	16.60 a y	20.04 a xy	21.05 a x

[1] Amendment means within day with different a, b, c letters are different at the 0.05 significance level.
[2] Day means within amendment with different x, y, z letters are different at the 0.05 significance level.

Table 6
Mass and nutrient values of cucumber seedlings grown in potting mix amended with different levels of algal turf scrubber (ATS) biomass or fertilizer (mean ± std. error)

Amendment	ATS biomass			Fertilizer		None
	2.8 g	5.6 g	11 g	1.25 g	2.5 g	
Applied N (mg pot^{-1})	126	252	496	60	120	0
Available N (mg pot^{-1})[1]	42	83	164	38	75	0
Applied P (mg pot^{-1})	20.4	40.9	80.3	31.5	63	0
Biomass (g DW pot^{-1})	2.98^{ab} [2] ± 0.79	4.35^{ab} ± 0.24	4.16^{ab} ± 0.19	3.18^{b} ± 0.06	4.55^{a} ± 0.23	0.99^{c} ± 0.06
N content (%)	0.73 ± 0.06	1.14 ± 0.09	1.94 ± 0.25	0.75 ± 0.02	1.03 ± 0.13	0.54 ± 0.02
Total plant N (mg pot^{-1})	25.2^{c} ± 2.8	49.7^{b} ± 4.1	80.7^{a} ± 10.2	23.5^{c} ± 0.80	46.9^{b} ± 5.3	5.4^{d} ± 0.40
Net plant N/applied N (%)	15.7 ± 2.2	17.6 ± 1.6	15.2 ± 2.0	30.2 ± 8.1	34.6 ± 4.8	–
P content (%)	0.34 ± 0.03	0.47 ± 0.08	0.82 ± 0.07	0.38 ± 0.02	0.51 ± 0.11	0.25 ± 0.00
Total plant P (mg pot^{-1})	11.8 ± 0.53	20.4 ± 4.0	33.8 ± 1.9	12.1 ± 0.56	23.4 ± 5.6	2.5 ± 0.13
Net plant P/applied P (%)	45.5 ± 2.6	43.8 ± 9.9	39.0 ± 2.4	30.5 ± 1.8	32.9 ± 8.9	–

[1] Available N values were calculated as 33% and 62.5% of TN for ATS biomass and fertilizer, respectively.
[2] Means with different letters are different at the 0.05 significance level.

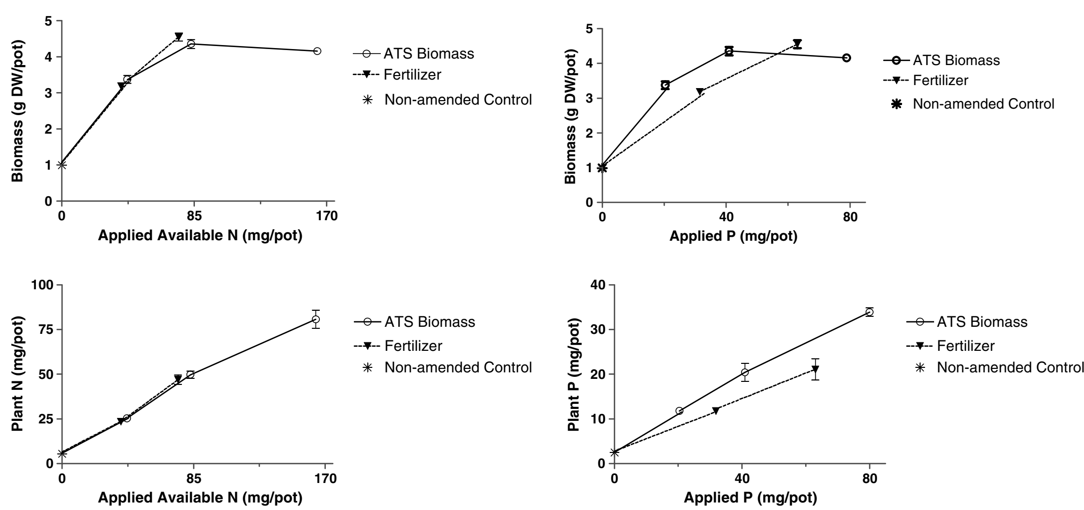

Fig. 2. Seedling mass, seedling N, and seedling P values of 20-day old cucumber seedlings grown in potting mix and in potting mix amended with different levels of either algal turf scrubber (ATS) biomass or fertilizer (mean ± std. error).

Table 7
Mass and nutrient values of corn seedlings grown in potting mix amended with different levels of algal turf scrubber (ATS) biomass or fertilizer (mean ± std. error)

Amendment	ATS biomass		Fertilizer		None
	10 g	20 g	5.5 g	11 g	
Applied N (mg pot^{-1})	451	900	264	528	0
Available N (mg pot^{-1})[1]	150	300	165	330	0
Applied P (mg pot^{-1})	73	146	138	275	0
Biomass (g DW pot^{-1})	6.8^{b} [2] ± 1.0	10.7^{a} ± 1.1	7.7^{b} ± 0.8	8.6^{ab} ± 1.2	0.53^{c} ± 0.11
N content (%)	1.39 ± 0.22	1.62 ± 0.13	1.44 ± 0.18	2.56 ± 0.20	0.62 ± 0.04
Total plant N (mg pot^{-1})	94.0^{c} ± 19.3	173^{b} ± 16.8	110^{c} ± 11.0	218^{a} ± 17.1	3.36^{d} ± 0.68
Net plant N/applied N (%)	20.1 ± 4.3	18.9 ± 1.9	40.3 ± 4.2	40.7 ± 3.2	–
P content (%)	0.66 ± 0.06	0.57 ± 0.03	0.72 ± 0.05	0.89 ± 0.11	0.86 ± 0.06
Total plant P (mg pot^{-1})	44.3 ± 5.1	61.4 ± 6.0	54.9 ± 3.7	75.4 ± 6.3	4.5 ± 0.7
Net plant P/applied P (%)	60.6 ± 6.1	42.0 ± 3.5	39.8 ± 2.7	27.4 ± 2.3	–

[1] Available N values were calculated as 33% and 62.5% of TN for ATS biomass and fertilizer, respectively.
[2] Means with different letters are different at the 0.05 significance level.

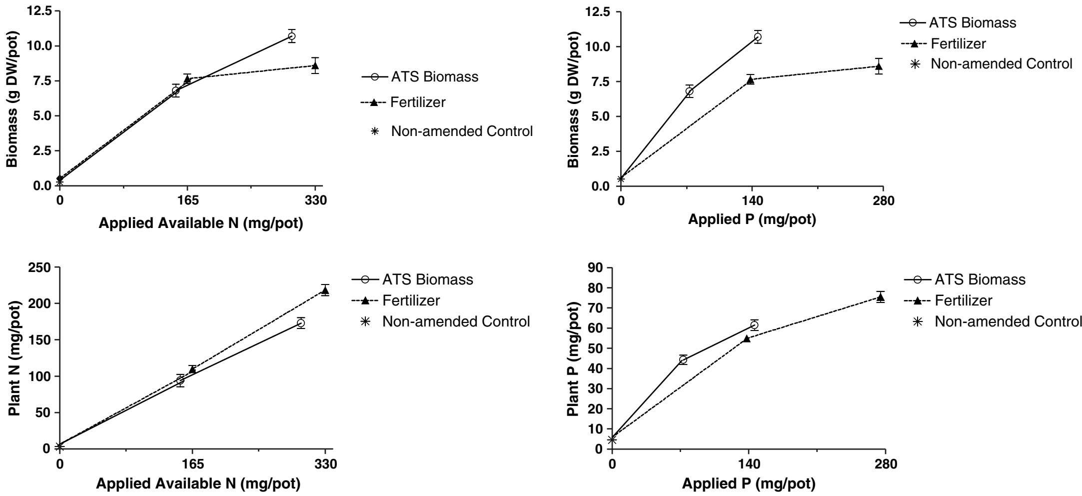

Fig. 3. Seedling mass, seedling N, and seedling P values of 20-day old corn seedlings grown in potting mix and in potting mix amended with different levels of either algal turf scrubber (ATS) biomass or fertilizer (mean ± std. error).

150 kg ha^{-1}. As a P fertilizer used for amending soils at 100 kg P ha^{-1} this volume of algal biomass would support 4 ha of production. At these amendment rates (6.5–10 mt biomass ha^{-1}), loadings of heavy metals from the algal biomass would be well below those permitted by the US EPA Part 503 biosolids rule (EPA, 1994).

We have not yet characterized the algal biomass with regard to levels of potential pathogens. Pathogen levels in the biomass would depend not only on levels in the manure being treated, but also on UV levels, pH and temperature in the shallow ATS raceways, as well as subsequent biomass drying and storage procedures.

Although the ATS biomass used in this study was from a small laboratory-scale system, larger scale ATS systems have been operated in aquacultural and wastewater facilities (Adey and Loveland, 1998) However, capital and operational cost estimates for these operations is very limited. There is more extensive experience with the cultivation of suspended algae in high rate algal ponds (Sheehan et al., 1998) and the engineering designs and cost estimates are much more well developed (Benemann and Oswald, 1996; Goh, 1986). Recent studies using high rate algal ponds have focused on treating manure effluents from swine (Olguin et al., 2001) and dairy operations (Craggs et al., 2003).

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